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All-Sky Monitor Observations of Flares from Aquila X-1

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ABSTRACT

The All-Sky Monitor on *Ariel* 5 has observed the Aquila-Serpens region on a quasi-continuous basis since launch in 1974 October. During this time Aql X-1 exhibited major flares in 1975 June and 1976 June, with the measured X-ray intensities increasing more than an order of magnitude to approximately that measured from the Crab nebula, and remaining above the experiment threshold ($\sim 0.1 \times S_{crab}$) for almost two months in both instances. These outbursts resemble the X-ray light curves of transient sources such as A0620-00 and are interpreted in terms of episodic accretion in a dwarf nova-like binary. Combination of the epoch of phase minimum for the $1\overset{d}{.}3$ period reported by Watson (1976a) with the 1975 data yields a value of $P = 1\overset{d}{.}28 \pm 0\overset{d}{.}02$ with a corresponding modulation of $\sim$ 3% (3-6 keV). Modulation at this period is not apparent in the 1976 data, with an upper limit of 2% during that time.

SUBJECT headings: X-rays: binaries - X-rays: transient sources
stars: dwarf novae

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I. INTRODUCTION

The variable nature of Aquila X-1 (3U1908+00) was suggested by early rocket observations in which the source was present only on an occasional basis in surveys of the region (cf. Seward 1970). Aql X-1 was also observed by *Uhuru*, appearing in the 3U catalog (Giacconi *et al.* 1974) as a source of moderate brightness and variability ($S \sim 0.07 - 0.2 \times S_{crab}$). OAO *Copernicus* subsequently reported the source at least an order of magnitude below the *Uhuru* range in intermittent observations over a two-year period through 1975 May (Davidsen *et al.* 1975). This apparent quiescent state was interrupted in 1975 June by a sudden flare (factor of $\gtrsim$ 20 increase, Buff 1975) to the level of the Crab nebula. Observations of the declining source by the Sky Survey Instrument (SSI) on *Ariel* 5 revealed an ∿10% sinusoidal modulation (2-18 keV) at the period $P = 1^{d}.3 \pm 0^{d}.04$ (Watson 1976a). By August the flux had decayed back to the pre-outburst intensity ($< .003 \times S_{crab}$) as measured by the SSI (Villa *et al.* 1976), which instrument observed the same low flux from Aql X-1 again in 1976 January.

In 1976 June, the All-Sky Monitor (ASM) on *Ariel* 5 detected an additional outburst of this source (Kaluzienski *et al.* 1976a) which was confirmed by the SSI (Watson 1976b). We report in this *Letter* ASM observations of Aql X-1 from the launch of *Ariel* 5 in 1974 October through 1976 August. The results of periodic analyses of the ASM flare data are compared with the SSI result, and the possible relation of the source to the class of optical dwarf novae is discussed.

II. EXPERIMENTAL RESULTS

The ASM consists of a pair of 1 cm^2 pinhole camera detectors which provide virtually continuous coverage of >80% of the X-ray sky in the 3-6 keV energy band. A complete description of the experiment can be found in Holt (1976). Temporal resolution is defined by the time for one orbit ($\sim$ 1.7 hours), and the inherently low counting rates frequently require accumulation of the single-orbit data into $\sim$ 1/2 day integrations in order to improve the experimental sensitivity. The experiment ordinarily operates in a mode with typical positional accuracy of $\sim$5°, but a mode with a factor of $\sim$ 4 times finer resolution is available on command. This latter mode is especially useful when source confusion or relatively high background conditions exist, but its use must be confined to only 1/16 of the sky (i.e., at the expense of all-sky coverage).

The proximity of Aql X-1 to the sources Ser X-1 (3U1837+04) and 3U1901+03 ($S_{max} \sim 0.3$ x and 0.1 x S_{crab}, respectively) make unambiguous detection of a low Aql X-1 flux ($\lesssim 0.2$ x S_{crab}) problematic in the ASM standard resolution mode. Consequently, occasional fluctuations in detector background and other systematic effects could conceivably result in "accidental" flux measurements (with low probability) as high as $\sim$ 0.3 x S_{crab} for this particular source. The data obtained during the 1975 and 1976 flares of Aql X-1 are illustrated in Figures 1 and 2 and represent the only unambiguous detections of the source over the $\sim$22 months of ASM operation during which the duty cycle for daily monitoring of the Aquila-Serpens region was > 75%. These plots consist of $\sim$1/2 day averages of the 3-6 keV flux (incident photons) with corresponding

$\pm$ 1σ statistical error bars (estimated 1σ systematic errors are smaller than the statistical uncertainties). The upper limits obtained (0.1 $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$) immediately prior to the 1975 flare are consistent with the SAS-3 observations, and no positive detections of the source above $\sim$0.2 $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ were made during the preceding 7 1/2 months. A similar search of the ASM data over the period between the flares yielded no unambiguous source sightings through 1976 April, with a possible detection at $\sim$0.3 $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ (for $\sim$1 day) two weeks prior to the 1976 outburst. We note finally that the apparently differing peak flux levels of the flares are actually consistent with a single limiting value ($S_{max} \approx 1.0 \times S_{crab}$), as a result of a possible degradation in the effective 3-6 keV detector efficiency of $\sim$ 10% occurring between the two flare observations.

Source periodicities were tested for by separately folding (in 10 bins) the single-orbit flare data at trial periods in the range $0\overset{d}{.}3$ - 5^{d} and noting deviations in the χ^2-period distribution (vs. hypothesis of source constancy). A peak in χ^2 is evident near $P = 1\overset{d}{.}3$ in the 1975 data, and the observed width of $\simeq \pm 0\overset{d}{.}07$ is consistent with that expected for a data sample interval of $\sim$25 days. The 1976 flare data, however, revealed no significant χ^2 deviations over the range of trial periods indicating the absence of any modulation in the $1\overset{d}{.}25$ - $1\overset{d}{.}34$ range in excess of $\sim$ 2% (the most significant deviation in the 1976 data is at $1\overset{d}{.}47 \pm \overset{d}{.}05$, with a corresponding modulation of $\sim$ 2%). The folded light curves obtained for the 1975 data in the range $1\overset{d}{.}3 \pm 0\overset{d}{.}04$ were examined for phase agreement with the SSI minimum (t_o = $1975.181\overset{d}{.}13 \pm 0\overset{d}{.}13$, Watson 1976a), which occurred for trial periods in the range $P = 1\overset{d}{.}28 \pm 0\overset{d}{.}02$. Folded light curves at this period for the two flares are shown in Figure 3 and imply decrements (at the respective light curve minima) of $\sim 0.028 \pm 0.007$ and $\sim 0.015 \pm 0.008$ (1σ errors) for the 1975 and 1976 data, respectively. We emphasize that the detection of such low-level modulation in the present data is marginal, as folds of similar data samples of the Crab nebula resulted in random χ^2 deviations comparable to those obtained for Aql X-1. Noting further that the degree of modulation may be a function of energy and/or flux level, we can conclude only that the ASM results are consistent with those of the SSI.

III. DISCUSSION

The similarity of the Aql X-1 flares reported here to the more extreme episodes of the transient X-ray sources has been pointed out by several observers (Kaluzienski et al. 1976b; Watson 1976a). The abrupt ($\lesssim$1 week) rise by ~2 orders of magnitude and subsequent gradual (e-folding time $\sim$ 1 month), nova-like decay back to the pre-flare level are reminiscent of the characteristic transient source light curves, apparently differing only in the degree of brightening (L_{max}/L_{min} for transients is, by definition, $\gtrsim 10^3$) and the absence of a clearly defined precursor peak. This behavior is, on the other hand, qualitatively different from the recurrent flares of Cyg X-1 (cf. Holt et al. 1976) or the extended "highs" (sometimes lasting for hundreds of days) exhibited by sources such as Cen X-3. In the context of a transient source association for Aql X-1, we note that the relatively soft flare X-ray spectrum (Davidsen 1975) suggests a generic relation to the class of "long-duration" transients (e.g., A0620-00, A1524-62, and A1742-28; Kaluzienski et al. 1976b), as opposed to the harder-spectral, shorter-lived transients exemplified by A1118-61 and A0535+26.

The flaring nature of Aql X-1, in which the bulk of the source emission is confined to well-defined, relatively low duty-cycle flares, is similar to the optical variations of the dwarf novae. We note also that the source behavior observed by Uhuru ($L \sim 0.07 - 0.2 \times L_{max}$, with no visible declining trend over $\sim$ 1 month; Jones 1976), while apparently inconsistent with a flaring episode, may be analogous to the "standstills" observed in several dwarf novae including Z Cam ($L_{standstill}/L_{max} \sim .3 - .5$; Osaki 1974). Since such "standstills" typically last longer than the mean flare cycle, relatively long periods of emission at the Uhuru level might be expected. In addition, the sporadic detection of Aql X-1 in the early rocket surveys (cf. Seward 1970) is not inconsistent with the picture of an eruptive source.

The X-ray and optical observations of Aql X-1 may be compared with the "X-ray dwarf nova" model suggested by Avni et al. (1976) for the transient source A0620-00 (Nova Monocerotis 1975). Although the report of a $7\overset{d}{.}8$ period for that source (Matilsky 1976) is apparently difficult to reconcile with a strict dwarf nova interpretation, the low eclipse probability ($\lesssim$ 37%) and relatively short binary period ($\lesssim 3^{d}$) expected in the Avni model are certainly consistent with the Ariel 5 observations of Aql X-1. Using the empirical period-amplitude relation for U Gem stars and recurrent novae of Payne-Gaposchkin (1957), the inferred luminosity ratio $L_{max} / L_{min} \sim 500$ (assuming that most of the radiation emerges in X-rays) yields an expectation value for the interval between flaring episodes of $\sim$465d. The uncertainty in L_{max}/L_{min} is more than enough to bring this expectation value into precise agreement with the observed flare interval, but we note that X-ray dwarf novae may deviate significantly from period-amplitude relations describing their optical analogues (c.f. Bath 1974; Avni et al. 1976). We can only conclude, therefore, that the observed flare interval is not inconsistent with that which might be expected from such a source.

The close similarity of the two flare light curves is also interesting, as it suggests detailed reproduceability. This characteristic of the source behavior can be reconciled with accretion dwarf nova models invoking relatively continuous mass transfer to an accretion disk which is eventually "dumped" by an instability (Osaki 1974) or, alternatively, quasi-periodic unstable Roche-lobe overflow of the red star (Bath et al. 1974). In the former model, the similarity of the flares results from the comparable amounts of material accumulated between episodes, while in the latter a high regularity of the magnitude of Roche-lobe spills and/or a feedback loop (regulated first by self-excited transfer and later by Eddington-limited flow) may be implied.

Based on the similarity of the X-ray behavior to A0620-00, we may estimate the optical magnitudes of the Aql X-1 system for comparison with observation. If the effective equality of the peak fluxes obtained in the flares is indicative of an Eddington-limited luminosity ($L_{max} \lesssim 10^{38} \frac{M_x}{M_\odot}$ erg sec^{-1}), a distance to the source of $D \lesssim 7$ Kpc ($M_x = 1 M_\odot$) is implied. Assumption of a roughly constant X-ray-to-optical flux ratio similar to that of A0620-00 and Sco X-1 ($L_x/L_{opt} \gtrsim 10^3$, Doxsey et al. 1976) yields an apparent visual magnitude at maximum of $m_{v_{max}} \sim 15 + A_v$ and a corresponding quiescent magnitude of $m_{v_{min}} \sim 20 + A_v$. These values are consistent with the failure to identify an optical counterpart down to $B = 17.5$ during the 1975 outburst (Davidsen et al. 1975) for modest absorption ($A_v \sim 3$) in this direction at the estimated distance

While the association of Aql X-1 with a dwarf nova-like system is apparently consistent with the existing observations, alternate interpretations of the present behavior are possible. In particular, if the $1\overset{d}{.}3$ variation does not represent an orbital period, a Mira variable-type binary ($P_{binary} \gtrsim 2$ yr, Fabian et al. 1975), consisting of a periodically expanding ($P_{expansion} \sim 0.3 - 3$ yr) giant and collapsed companion, could conceivably account for recurring, replicating flares on such a relatively long timescale. Such systems have been associated with the transients 3U1543-47 (Forman and Liller 1973; Li et al. 1976) and A1118-61 (Fabian et al. 1975), but recurrent outbursts at the period of the latter's suggested optical counterpart were not observed (Davison and Sanford 1976). In the present case, the lack of a known Mira variable (to $m_v \sim 11$) within a few degrees of Aql X-1 (cf. Merrill 1941) is not irreconcilable with the observations, since even at maximum light (assuming $M_{v_{max}} > -3$) the primary may be undetectable at the source distance estimated above. It is also interesting to note that interpretation of the present data in terms of an eccentric, long-period binary model suggested for several transient sources (McCluskey and Kondo 1971; Tsygan 1975;

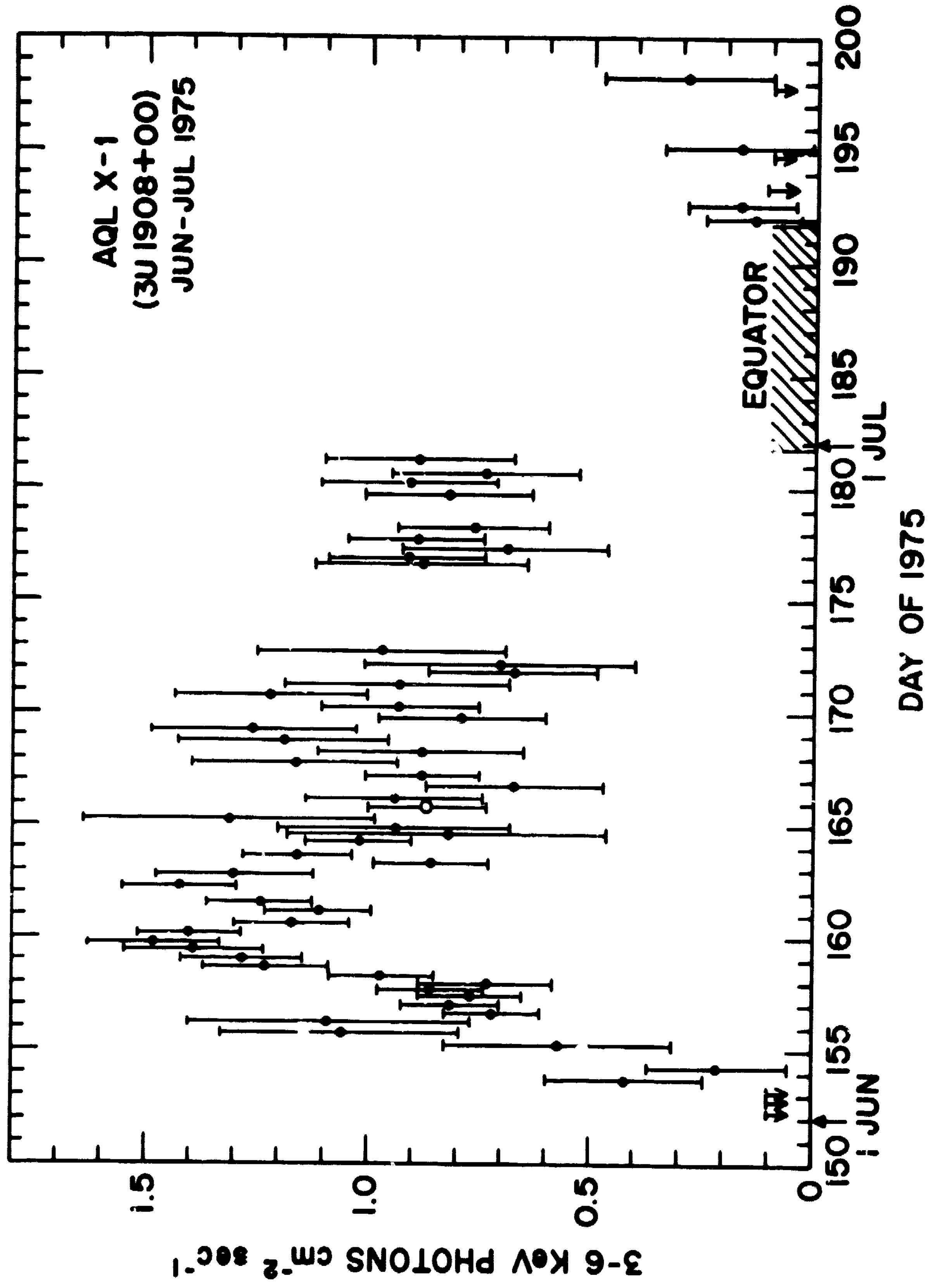
Pacini and Shapiro 1975) is difficult to reconcile with the quiescent inter-flare emission and would further require a relatively large eccentricity e $\sim$ 0.9 (cf. Avni *et al*. 1976). Finally, it should be pointed out that although the behavior reported here has been interpreted in terms of *physical* flaring of the source, we cannot rule out a modulation similar to that responsible for the 35^d cycle of Her X-1, which may be precessionally induced (Brecher 1972; Roberts 1974; Petterson 1975).

FIGURE CAPTIONS

Figure 1 1975 flare of Aql X-1. The points represent $\sim 1/2$ day averages and error bars reflect the $\pm 1\sigma$ statistical uncertainties. Open circles denote measurements obtained in the "fine" spatial resolution mode (see text) of the experiment. The shaded area indicates the interval during which the source was observed by the SSI and therefore inaccessible to the ASM. Additional gaps in coverage are due primarily to confusion with Ser X-1.

Figure 2 1976 flare of Aql X-1. See description of Fig. 1.

Figure 3 Folds of single-orbit data at the trial period $1^{d}.28$ for the 1975 (upper trace) and 1976 (lower trace) flares. The shaded region is centered on the minimum phase of the modulation reported by Watson (1976a). A slight adjustment of the period by $\sim .0007^{d}$ can bring the 1976 decrement into phase agreement with that of the 1975 data but,as discussed in the text, the 1976 modulation is not statistically significant.

AQL X-1
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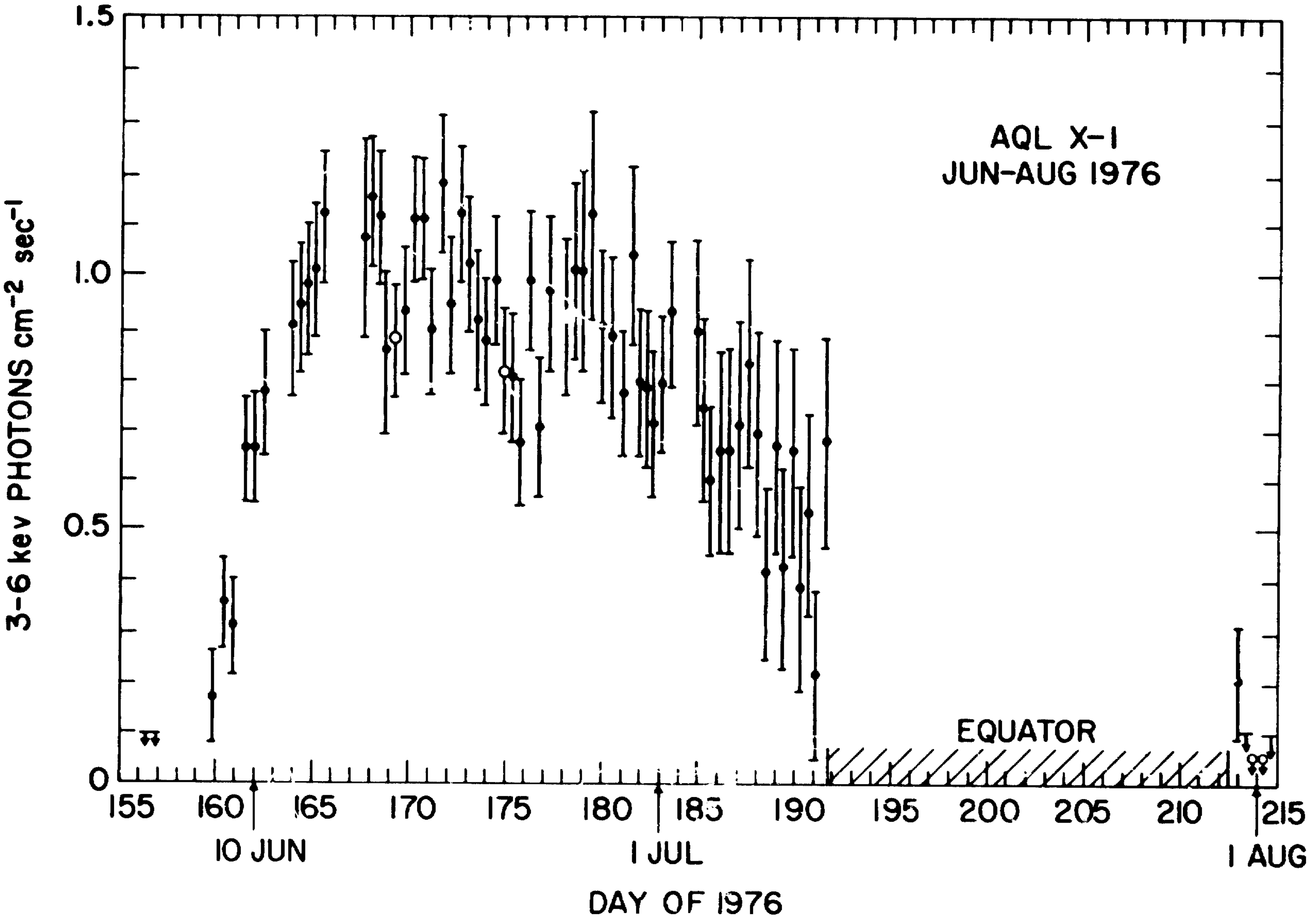
1.5
DAY OF 1975
150
155
160
165
170
175
180
185
190
195
200
1 JUN
1 JUL


AQL X-1
JUN-AUG 1976
3-6 kev PHOTONS cm^{-2} sec^{-1}
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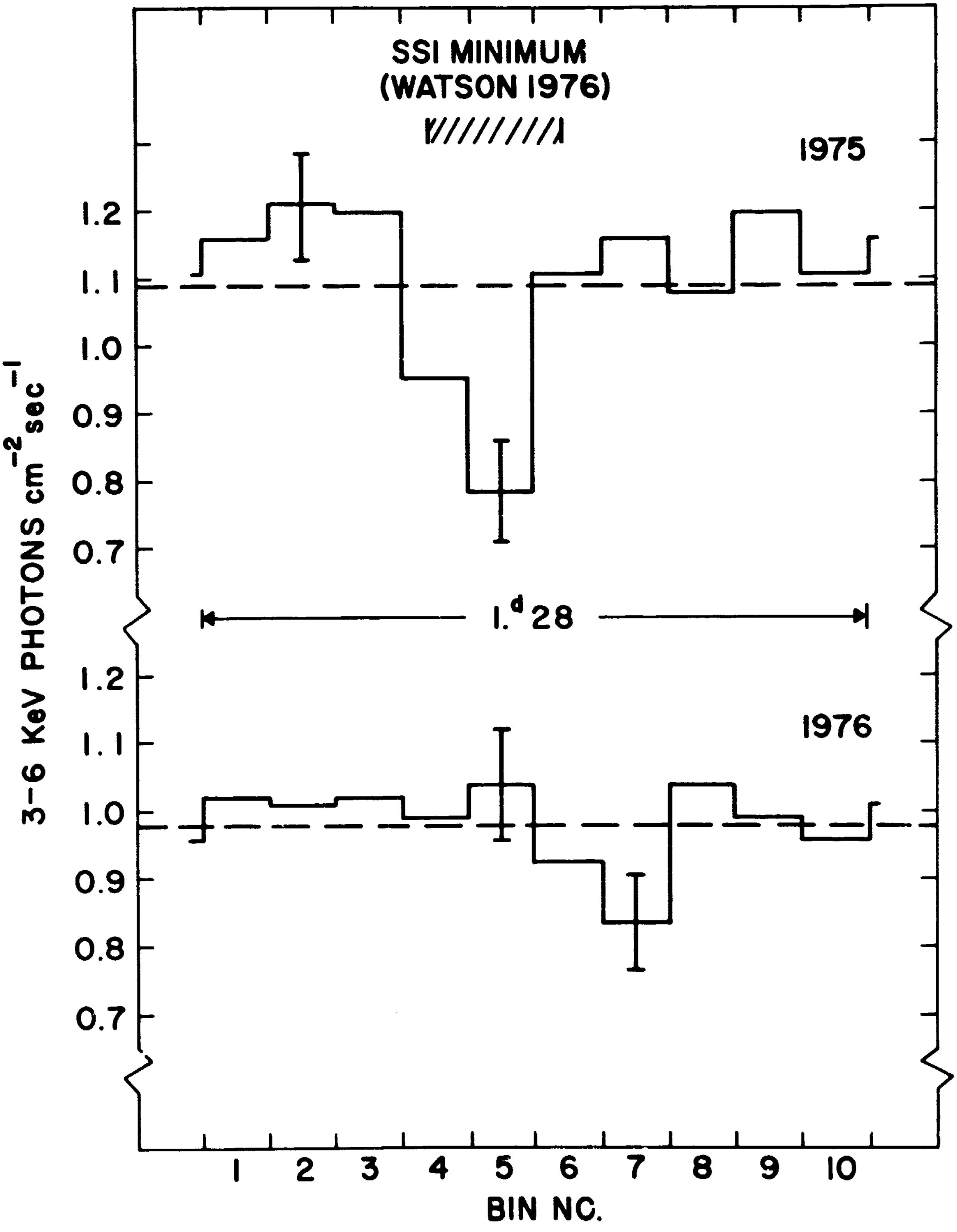
DAY OF 1976
EQUATOR


SSI MINIMUM
(WATSON 1976)
1975
1976
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3-6 KeV PHOTONS cm⁻² sec⁻¹
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0.9
0.8
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2
3
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